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L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Ray Tracing in the Troposphere, Ionosphere and Magnetosphere

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United States Air Force

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IONOSPHERIC PHYSICS LABORATORY PROJECT 5631

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Abstract

Ray patterns are presented which delineate the propagation of radio signals to large distances by ducting under super-refracting conditions in the troposphere, ionosphere, and magnetosphere. The unity of ducting is emphasized in the sense that the ducts, whether they occur in the troposphere, ionosphere, or magnetosphere, all have formally similar features. This unity follows from the circumstance that the rays which propagate to large distances are those which graze a super-refracting layer at shallow glancing angles and which generally traverse only those regions of the propagation medium where the refractive index deviates but slightly from the free-space value.

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Ray Tracing in the Troposphere, Ionosphere, and Magnetosphere

I. INTRODUCTION

Since the beginning of radio, ray theory has been in use for elucidating the transmission of radio waves to large distances via the ionosphere. By 1935, theorists had derived the basic theorems, on the basis of ray theory, for ionospheric propagation under the particular situation of an ionosphere which is spherically symmetric (an ionosphere in which the electron density varies only with altitude and not with horizontal distances).

World War II gave great impetus to radio propagation investigations because of pressing requirements for communication channels via the ionosphere and also because it was discovered that shortwave radars can, when super-refracting layers occur in the troposphere, have coverages extending to distances far beyond the expected line-of-sight ranges. It was then that ray tracing by computer developed in England by use of a differential analyzer (an analog type of computer which had been invented by Vannevar Bush at M. I. T.) for solving the ray-tracing equations (Hartree et al, 1946). Computers have been a useful tool for investigating practical problems of radio propagation under all types of ducting conditions.

In 1959, T. Obayashi suggested, by analogy with tropospheric radio ducts, the possibility of trapping high-frequency waves in magnetospheric ducts (channels

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of enhanced ionization aligned with the earth's magnetic field lines in the magnetosphere).

2. RAY PATTERNS

A group of representative ray patterns is presented here to delineate the propagation of radio signals to large distances beyond line-of-sight, which is of practical consideration to Air Force operational problems, under ducting (super-refracting) conditions in the troposphere, ionosphere, and magnetosphere.

The rays which propagate to large distances are those which graze a refracting layer at shallow glancing angles and which generally traverse only those regions of the propagating medium where the refractive index deviates but slightly from unity. Since only relatively small deviations of the refractive index from unity are involved, the characteristic features – the radio ducts, ray-scarce and ray-concentrating regions – which appear in the ray patterns shown here are all very similar, independently of whether they occur in the troposphere, ionosphere, or magnetosphere.

A ray pattern in the vertical plane, with the altitude plotted vertically and the distance along the spherical earth's surface plotted horizontally, shows the distribution in this plane of rays emitted from a radio transmitter which is represented as a point source.

Figures 1 and 2* are patterns in the troposphere. A single, horizontally-uniform layer occurs in Figure 1 where the refractive index decreases rapidly as a function of height, with a resulting change in refractive index of 40 N-units (40×10^{-6}); the propagating medium above and below this layer is assumed to have the standard refractive-index gradient of -12 N-units per 1000 ft. Figure 2 corresponds to more realistic, experimentally-measured conditions with the refractive-index gradient vs altitude profile as shown at the right-hand border of the figure; this profile is assumed also to remain unchanging with distance for the 320 miles shown.

Figures 3 and 4 are ionospheric ray patterns (Haselgrove, 1955). For Figure 3, the electron density vs altitude profile consists of an F2 layer peak and a ledge in the F1 region. The maximum electron-density peak and the altitude where this peak occurs both vary with distance as shown by the curves labeled $N_m(D)$ and $h_m(D)$, respectively. The radio wave frequency is 14 MHz, and the earth's magnetic field is omitted in Figure 3.

Figures 4a and 4b are examples of 3-dimensional ray tracing, showing the projections of one ray upon a vertical (altidude vs colatitude THETA) plane, (Figure 4a), and upon a horizontal spherical (longitude PHI vs colatitude THETA

*Figures 1, 2, 3 and 5 were computed and plotted by analog computers.

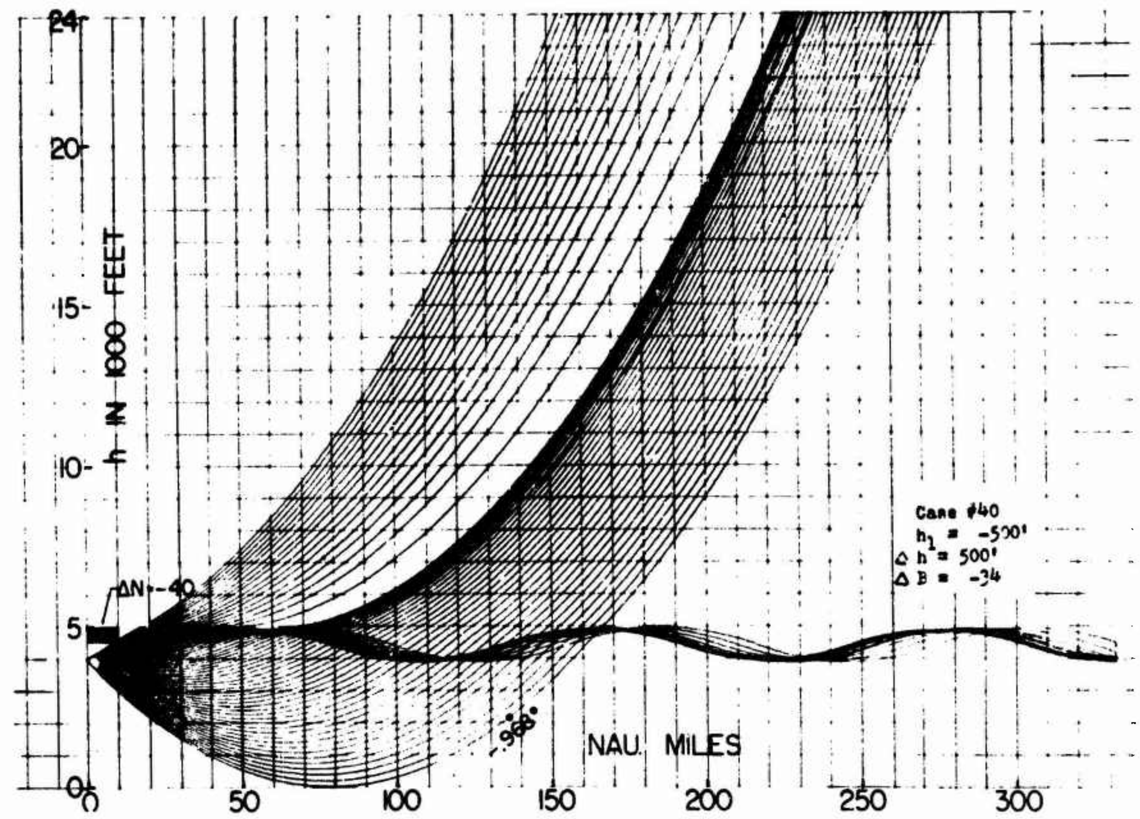

Figure 1. Tropospheric Ray Pattern for a Prototype Refractive-Index Profile

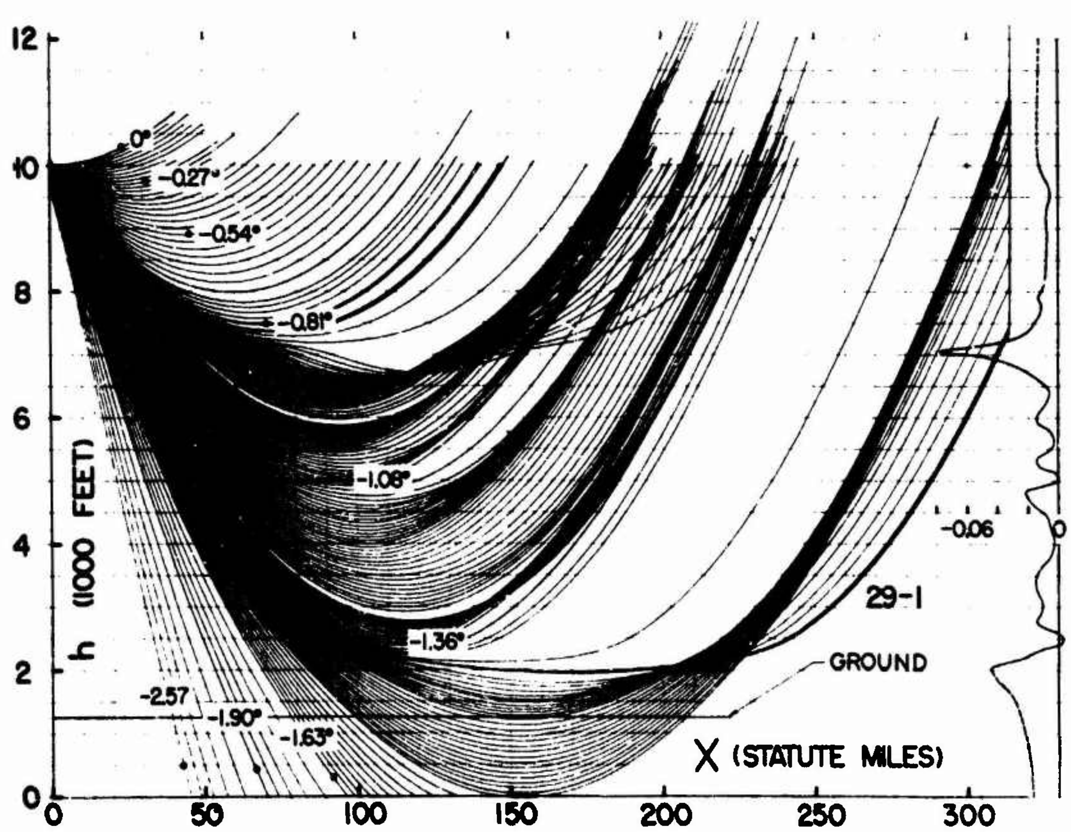

Figure 2. Tropospheric Ray Pattern for a Realistic Refractive-Index Profile

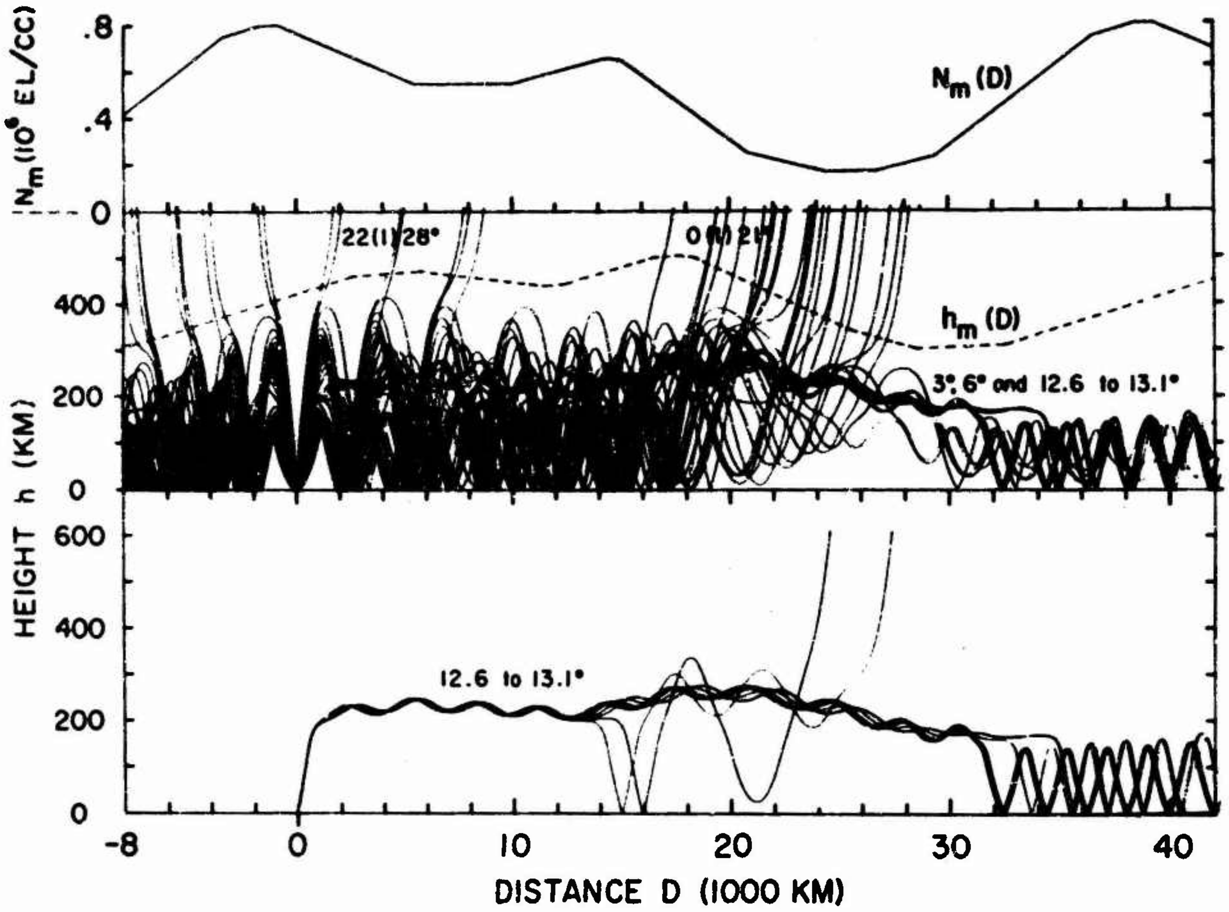

Figure 3. Ionospheric Ray Pattern with Rays (repeated at bottom) Trapped for 32,000 Km in an Elevated Duct

surface (Figure 4b). The frequency is 34.3 MHz. The magnetic field is included as an earth-centered dipole field. The ray shown in Figures 4a and 4b is for the magneto-ionic ordinary mode. The electron density distribution is an idealized, 3-dimensional global model in which the electron density varies with height as a Chapman profile having two electron-density peaks (one north and the other south of the geomagnetic equator) in each meridian plane on the day half of the ionosphere and in which there is a single peak in each meridian plane on the night half of the ionosphere. The ray shown starts at an altitude of 298 km, at colatitude = 98.5 deg (latitude = 8.5 deg south) and longitude = 180 deg east; travels in a north-westerly direction to a position at colatitude = 59 deg and longitude = 78 deg east; and from this position travels in a south-westerly direction to the final ray position at an altitude of 142 km, at colatitude = 98.0 deg and longitude = 30 deg west (210 deg west of the initial longitude). The ray path appears to undergo a complicated excursion in the latitude-longitude plane; this is due only to the fact that a flat sheet is used to represent geographical (spherical) coordinates. In reality, the ray remains closely near a great-circle plane.

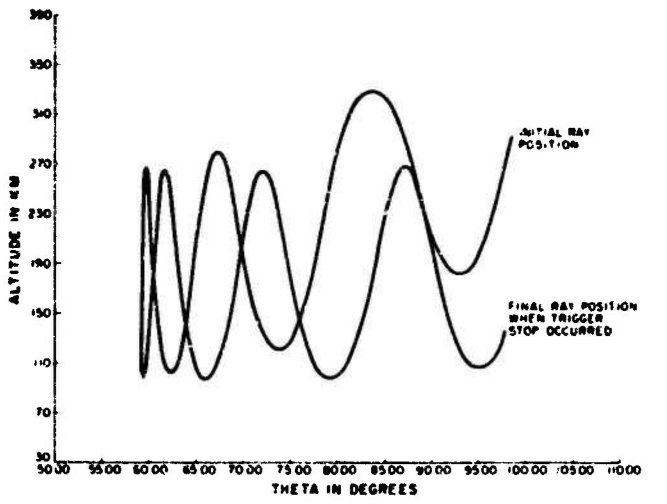

Figure 4a. Sample Ionospheric Ray Projected on Vertical Plane

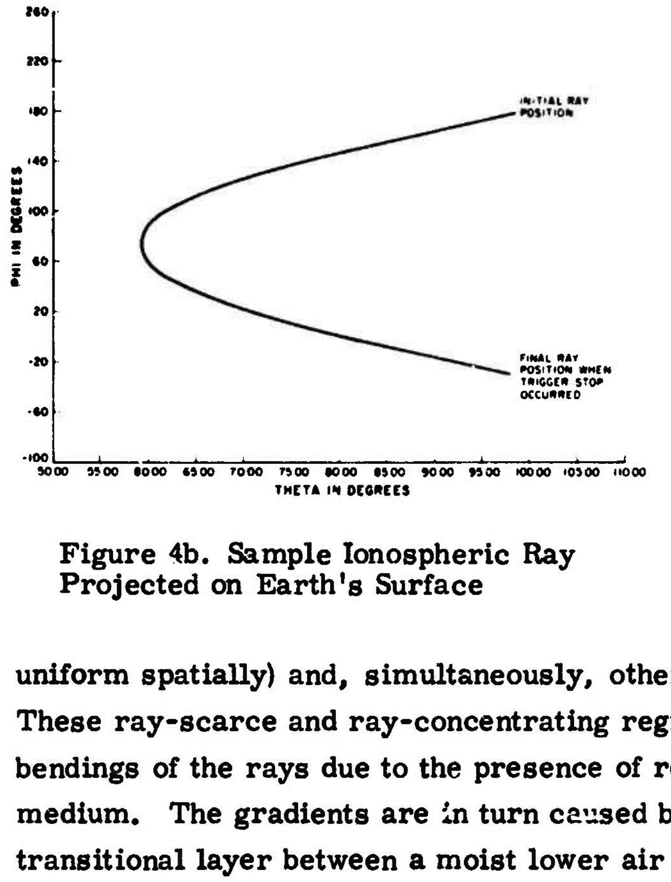

Figure 4b. Sample Ionospheric Ray Projected on Earth's Surface

Figure 5 shows the trapping of some rays, emitted from a transmitter at the earth's surface at 50-deg north geomagnetic latitude, in a radio duct aligned with a thin band of field lines of the earth's magnetic field. The trapped-ray paths undergo chordal reflections by the transverse electron-density gradients at the trapping field lines at altitudes above the ionospheric F region; below the F region, all the rays follow ordinary ray paths (approximately straight lines). Within the F region, an appropriate variation of electron density is required in order to initiate the trapping of rays in the field-aligned duct. Also, a thin layer of enhanced ionization, aligned with the thin band of trapping geomagnetic field lines, is required in order to sustain the trapping of the rays to the conjugate region in the southern hemisphere.

A prominent feature in ray patterns is the occurrence of regions of decreased ray density (compared with the ray density if the propagating medium were uniform spatially) and, simultaneously, other regions of increased ray density. These ray-scarce and ray-concentrating regions are caused by progressive bendings of the rays due to the presence of refractive-index gradients in the medium. The gradients are in turn caused by moisture variation (such as in the transitional layer between a moist lower air mass and an overlying dry air mass) in the troposphere and by varying ionization in the ionosphere.

Trapping of rays in a radio duct occurs usually when the transmitter is located within, or not too far below, a super-refracting layer (where the refractive index varies negatively with height at a rate larger in magnitude than $1/r$, where r is the radial distance from the earth's center to a point in the duct). However,

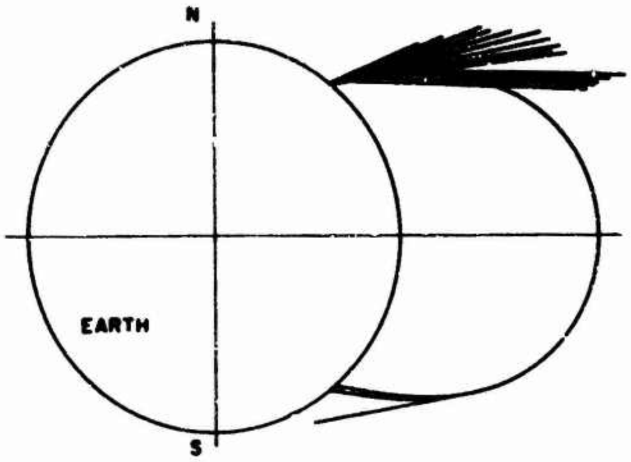

Figure 5. Ray Pattern with a Magnetospheric Duct

when appropriate gradients parallel to the duct prevail, as in Figures 3 and 5, the transmitter may be 200 km or more below the super-refracting layer, and some of the rays from the transmitter can still be trapped in an elevated duct. Under proper circumstances, some rays from a transmitter 200 km above the layer can also be trapped in a duct. Whenever a duct occurs, a ray-scarce region, and, simultaneously, a ray-concentrating region occur above the duct. Ray-scarce and ray-concentrating regions occur whenever the transmitter is within or anywhere above a layer with a negative refractive-index (not necessarily super-refractive) gradient.

3. FUTURE DEVELOPMENT

At present, it takes three minutes on a large digital computer to compute a ray going halfway around the world (20,000 km) if the earth's magnetic field is included as a centered dipole field and if the ionosphere is represented by an idealized, 3-dimensionally-inhomogeneous model. It is anticipated that, with the rapidly advancing state of computer capabilities, it will be practical to compute an entire ray pattern and display this pattern on an oscilloscopic screen in a few minutes. This eventuality will provide a capability of obtaining, at near real-time, a panoramic assessment of radio propagation conditions in the high frequency band for radars or communication circuits over a large operational region. For example, in tracking a target, a radar has to make observations over a wide range of azimuthal directions. The ionospheric electron-density distribution in the vertical plane of each azimuth varies from one azimuthal direction to another so that the ionospheric data have to be fed into the computer rapidly, and a sequence of ray patterns for various frequencies has to be displayed in rapid succession if synoptic ionospheric data are to be used effectively in any near real-time assessment of high-frequency radio propagation conditions in the operational region of the radar. An important factor in this assessment is the occurrence, and locations, of the rays escaping upward from a duct at various intervals of distance from the transmitter as shown in Figure 3.

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